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STATISTICAL-DYNAMICAL PREDICTION OF TROPICAL CYCLONE MOTION (NHC73)

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ABSTRACT

This paper describes the development of a new statistical model (to be known as NHC73) for the prediction of tropical cyclone motion. Multiple screening regression techniques are used with the "perfect-prog" concept to introduce numerically forecast upper-air data into the prediction equations. In this respect, NHC73 differs from earlier statistical models developed for the National Hurricane Center which use only current and 24-hour old height data as predictors.

A distinguishing feature of the new model is the use of an optimized areal stratification system. The Atlantic, Caribbean and Gulf of Mexico are subdivided into 52 zones. Using overlapping sets of dependent data, a separate set of prediction equations is developed for each of these zones. Such a procedure minimizes discontinuities in the forecast storm track which can otherwise occur when the system shifts from one set of prediction equations to another.

Based on dependent data, NHC73 performs considerably better than previous statistical systems. However, the use of operational prognostic data in lieu of the "perfect-prog" data will certainly degrade the results. The actual amount of degradation must await testing the system in an operational environment.

1. INTRODUCTION

A. Review of current prediction models

With reference to the Atlantic, Caribbean and Gulf of Mexico area, a number of recent papers describe both statistical and dynamical models for the prediction of tropical cyclone motion. The National Hurricane Center (NHC) uses a number of these techniques as objective guidance preparatory to the issuance of tropical cyclone advisories.

The NHC67 system (Miller, et al, 1968) has been in use at NHC for a number of years. Zonal and meridional components of storm motion are predicted separately from a series of multivariate regression equations derived through standard stepwise screening procedures. Predictors include various linear combinations of observed height and height change fields at the 1000, 700, and 500-mb. surfaces. Persistence is also used as a predictor in the early forecast periods.

The Sanders barotropic (SANBAR) model is described by Sanders and Burpee (1968). SANBAR is a filtered barotropic model using input derived from a grid representation of the observed 1000 to 100-mb. pressure weighted winds. Although some subjective analyses are required to augment the wind field in sparse data regions, the system, as originally conceived, does not use any persistence. However, Pike (1972) showed that modifying the wind field near the storm to conform to the observed storm motion substantially improved verification statistics for the 1971 hurricane season. Accordingly, Pike's modifications were incorporated into the system prior to the 1972 season.

HURRAN, developed by Hope and Neumann (1970) is an analog system. All recorded tropical cyclone tracks after the year 1885 are computer scanned and those with time and space characteristics similar to a current storm are identified and translated to a common origin. The cluster of analog storm positions at the various time intervals are then fitted to a bivariate normal distribution, the centroids of which represent the forecast track. A detailed error analysis of HURRAN is given by Neumann and Hope (1972).

CLIPER (Neumann, 1972) is a purely statistical technique used for the first time during the 1971 hurricane season. Originally intended as a back-up for HURRAN when the latter failed to find sufficient analogs, the system makes explicit use of climatology and persistence. A series of non-linear multiple regression equations are fitted to essentially the same predictors used in the analog sense by HURRAN.

The HATRACK system described by Renard (1968), uses a geostrophic steering concept applied to heavily smoothed analyses and prognoses produced by the Fleet Numerical Weather Central, Monterey, California. A type of persistence is injected into the system by the application of a "bias" correction to the forecast after observing the error of the predicted track for the first 12 hours.

Operational use of these five systems has highlighted certain advantages and deficiencies inherent in each. Neumann and Hope (1973), studied errors associated with the statistical models and note that systems typified by HURRAN and CLIPER, that is, those lacking any current synoptic data input perform quite well in southerly latitudes. On the other hand, systems typified by NHC67 which require current synoptic upper air data, are needed if one is to successfully predict tropical cyclone motion out of the "tropics". The authors conclude that any optimized statistical forecasting scheme must somehow mesh the better features of both types.

Accordingly, the NHC72 system (Neumann, et al, 1972) was developed. This model uses a modified stepwise screening technique to incorporate the better features of HURRAN, CLIPER and NHC67 into a single system. NHC72 was used initially during the 1972 tropical cyclone season.

B. Use of prognostic data

With the exception of the HATRACK system, none of the aforementioned statistical models utilize prognostic data from numerical models. NHC67 and NHC72 are capable of predicting anomalous tropical cyclone motion but only if the anomaly is reflected in the current analysis. However, atypical progression of upper level troughs and ridges and their effect on tropical cyclone motion cannot be anticipated by these models and poor extended forecasts are apt to result. The primary purpose of a new system (to be known as NHC73) is to utilize the output of a numerical model such as the NMC primitive equation (PE) model (Shuman and Hovermale, 1968) in the prediction equations. The highly anomalous 1972 tropical cyclone season (Simpson and Hebert, 1973) highlighted the need for the inclusion of prognostic data in the statistical forecasting models.

Julian and Murphy (1972), discuss two modern techniques which have been successfully used for introducing numerical prognostic data into statistical models. One of these techniques, the so-called "perfect-prog" method is perhaps best exemplified by the work of Klein (1966) in maximum and minimum temperature prediction. The other method known as MOS for Model Output Statistics (for example, Glahn and Lowry, 1972) is also being successfully used in operational forecasting.

In the perfect-prog method, observed values of a predictor at time $T_o + \Delta T$ are used to derive a statistical relationship between predictor and predictand at the same time $T_o + \Delta T$. In actual practice, of course, forecast values of the predictors must be used and, therefore, any forecast error or bias is passed on to the statistical system.

In the MOS technique, actual prognostic data from a model are used to develop the prediction equations. Although MOS has certain advantages over the perfect-prog method in that biases of the numerical model are statistically corrected, and certain inaccuracies are recognized, its use, like any other statistical system, requires a certain amount of learning (dependent) data to insure statistical significance. Tropical cyclones are a relatively rare event and it is considered doubtful that a large enough sample of tropical cyclone forecast situations and concurrent PE prognostic grid-fields could be collected at this time. Veigas (1966) conducted an experiment on the use of the MOS concept in the prediction of hurricane motion. Failure of the experiment was attributed to a lack of sufficient dependent data. In this same study, Veigas used 24-hour NWP barotropic prognostic heights for the years 1962 and 1963 to test the performance of a system of prediction equations developed from the perfect-prog concept. The results of this latter test were much more successful than the MOS experiment but were still somewhat disappointing in the forecasting of meridional motion. It is considered likely that improvements in numerical prognoses over the years will circumvent some of the difficulties experienced by Veigas. For this reason, the perfect-prog concept, rather than the MOS approach was used in the NHC73 system.

C. General description of the NHC73 system

Most of the reduction of variance of current statistical tropical cyclone prediction systems is derived from predictors or predictor functions which deal with a) climatology and persistence, b) a geostrophic steering concept, or c) the position and intensity of the synoptic scale pressure systems which surround a storm. The NHC73 system involves the computation of a separate set of prediction equations using predictors from each of these three categories. Figure 1 illustrates the basic algorithm. Predictors selected from such non-synoptic variables as current storm motion (in the form of u and v components).

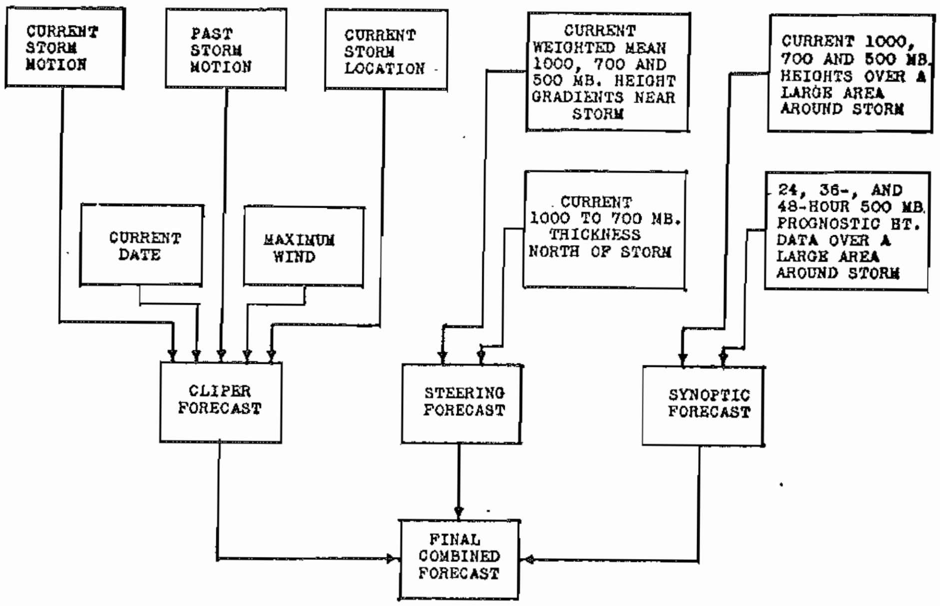

Figure 1. Schematic of the NHC73 tropical cyclone prediction system

past storm motion, current storm location, current day number and the maximum wind in the storm are used initially to produce a climatological CLIPER forecast. Next, the current height gradients and thicknesses near the storm are used to derive a separate set of predicted displacements based on steering considerations. Finally, the current and forecast upper air grid height fields over a large (2100 by 4200 n.mi.) area are analyzed so as to provide a third set of predicted displacements based on synoptic scale features.

Once the three sets of predictions are available, another set of prediction equations supplies appropriate weighting factors for the computation of a final displacement forecast. As will be discussed in Section 2D, these weighting factors, in the form of regression coefficients, vary widely, depending on time and space considerations.

The intermediate step of obtaining three separate sets of forecasts departs from traditional statistical concepts. Typically, all the predictors would have been analyzed at one time in a so-called stepwise screening procedure of the type described by Efroymson (1964). However, because of differences in the dependent and the independent data, it was felt that much valuable information would have been lost. For example, using best-track[1] data, the 12-hour CLIPER zonal forecasts are capable of explaining up to 96 percent of the variance of tropical cyclone motion. Because of inter-correlations in the data, additional predictors are ignored by the stepwise screening procedure. However, under operational conditions, the speed and direction of a storm are not known as precisely as one might hope for and predictors from another source (for example, the geostrophic steering around the storm) are often needed to counteract a bad initial motion input. If the dependent and independent data were known with the same order of accuracy, then such a procedure would not be warranted.

In summary, the NHC73 system computes three independent sets of forecasts. Each set consists of five pairs of zonal and meridional displacements for the period zero to 12 hours, zero to 24 hours, zero to 36 hours, zero to 48 hours and zero to 72 hours. One set, hereinafter referred to as the CLIPER set is based solely on predictors selected from non-synoptic sources. Another set, hereinafter referred to as the steering set, is based entirely on currently observed height gradients and thicknesses near the storm. The final set, hereinafter called the synoptic set, is based on the large scale observed and forecast pressure heights. The three sets of forecasts are then statistically combined into a final NHC73 set using additional regression coefficients as weighting factors.

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[1]The best-track positions are the accepted storm positions after a post-storm analysis.

2. COMPONENTS OF THE NHC73 SYSTEM

A. The CLIPER forecasts

The CLIPER system (Neumann, 1972) derives its variance reducing potential from eight basic empirical predictors as listed in Table 1. An additional 156 secondary predictors are generated by considering all of the possible second and third-order products and cross-products of the original eight predictors. The secondary predictors are of the form P_iP_j, $P_iP_jP_k$, P_i^2, P_i^3, etc. where the

Table 1. The eight basic predictors of the CLIPER system

P(I)	PREDICTOR
P(1)	Initial longitude (degrees)
P(2)	Initial latitude (degrees)
P(3)	Initial zonal motion (knots, E to W is pos.)
P(4)	Initial meridional motion (knots, S to N is pos.)
P(5)	Zonal motion 12 hours ago
P(6)	Meridional motion 12 hours ago
P(7)	Maximum wind in miles per hour
P(8)	Day number (135 through 334)

subscripts refer to a predictor number listed in Table 1. Normal stepwise screening techniques were used to select the most significant of the total 164 basic and higher predictors. Equation (1), for example, gives the 72 hour zonal CLIPER forecast (DX_{72}) displacement in n. mi. with the units of the predictors as given in Table 1,

$$DX_{72} = -60.3 +46.26(P_3) -8.81(P_5) +29.12(P_2-24) +32.91(P_4)$$
$$-0.022(P_4)^2(P_5) -0.086(P_2-24)(P_4)(P_5) +3.29(P_1-68). \quad (1)$$

The complete set of prediction equations, one for each component of storm motion at 12 hourly intervals can be found in the previously cited reference.

In spite of the lack of current synoptic data input, the CLIPER system gives results quite comparable to other statistical schemes in which climatology and persistence are used implicitly or not at all. On the average, most tropical cyclones behave quite normally and the explicit use of empirical predictors in CLIPER explains a major portion of the variance of tropical cyclone motion. Based on the original dependent data set using 3,156 tropical cyclone situations dating back through the year 1931, the CLIPER equations explain 96 percent of the variance of 12 hour zonal tropical cyclone motion decreasing to 75 percent of the variance at 72 hours. In the case of meridional motion, the reduction varies from a high of 91 percent at 12 hours to 45 percent at 72 hours. The greater reduction of variance in the case of zonal motion is typical of that attained by statistical forecast schemes. As pointed out in the preceeding section, a considerable portion of this variance reducing potential is lost since, at the time the forecast is made, the actual motion is not known with sufficient precision.

B. The steering forecasts

Miller and Moore (1960), in a paper dealing with the steering concept point out that the motion of a tropical cyclone is not determined solely by forces acting at any one level but rather by the mean wind flow integrated through a deep layer and over a substantial area surrounding the storm. The authors also point out that internal forces, propagation and probably some other factors also contribute to storm motion.

Due to the uncertainties of the above cited variables in an operational environment, numerical treatment of the steering principle has met with only limited success. It is doubtful that steering, by itself, can produce a satisfactory statistical forecast. However, since it does provide some incremental reduction of variance, the steering principle was retained as one of the components of the NHC73 system.

Prior to the adoption of a suitable steering function, considerable testing and pre-screening runs were made. Available for a statistical screening analysis were 317 hurricane forecast situations with concurrent

1000, 700, and 500 mb. heights at the 81 grid points in the 9 x 9 grid illustrated in Figure 2. Initial test screenings using meridional and zonal gradients taken over various distances established that, on the average, most of the steering "information" was contained in the row of grid-points 450 n.mi. around the storm (numbered grid-points 1 through 24 in Figure 2). This grid is in general agreement with that used by Miller and Moore (1960) and by Miller, et al (1968) in the NHC67 tropical cyclone prediction system. The testing further indicated, however, that somewhat better results were obtained by considering the gradients across a 300 n.mi. distance centered on a single grid-point rather than averaging across the storm, as was done in the above cited references.

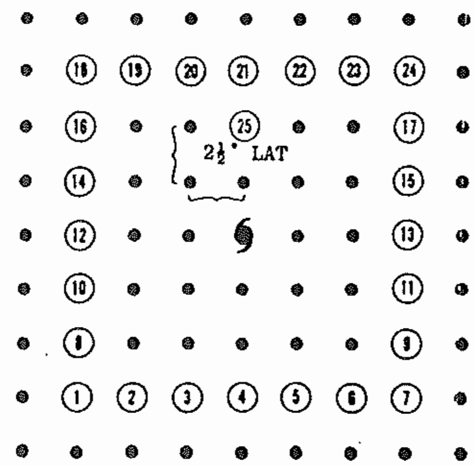


Figure 2. Grid used for steering computations

It was also found that greater variance reductions were realized by vertically weighting the grid data before computing any gradients where the vertical average height ($\overline{HT}$) at grid-point j was given by,

$$\overline{HT}(j) = [(H10(j) + 2\ H07(j) + 3\ H05(j)]\ /6, \qquad (2)$$

and where the designators H10, H07, and H05 refer to the observed heights at 1000, 700 and 500 mbs. The particular weighting function was selected after testing numerous other combinations of weighting factors. Poorest results were obtained from a function which weighted the 1000 mb. level 100 percent.

Two height gradients were computed for each of the grid-points labeled 1 through 24 in Figure 2. The east/west gradient (G_{ew}) at grid-point 21, for example was given by,

$$G_{ew}(21) = \overline{HT}(20) - \overline{HT}(22); \tag{3}$$

while the north/south gradient (G_{ns}) at grid-point 13 was given by,

$$G_{ns}(13) = \overline{HT}(11) - \overline{HT}(15). \tag{4}$$

Thus, a total of 48 gradients were available for the steering screening analysis. Since thickness considerations also relate to steering, an additional thickness ($\overline{T}$) predictor was computed from the average 1000 to 700 mb. thickness north of the storm,

$$\overline{T} = (T_{16} + T_{25} + T_{17})/3 \tag{5}$$

where the subscripts refer to grid-points referenced on Figure 2. However, the screening program failed to select thickness as a suitable predictor except in the case of 72 hour meridional motion.

The variance analysis, prediction selection order and regression coefficients for the final steering prediction equations are given in Tables 2 and 3. The general form of the prediction equation is given by,

$$D = C_o + C_1P_1 + C_2P_2 \ldots\ldots\ldots + C_nP_n \tag{6}$$

where D is any displacement, C_j refers to the regression coefficient ($j = 0,n$) and P_j refers to the corresponding predictor. In particular, the 12-hour meridional displacement (DX_{12}) in n.mi. is given by,

$$DX_{12} = 46.4 - 1.308G_{ew}(17) - 2.371G_{ew}(12) - 1.511G_{ew}(2) + 1.539_{ns}(8) \quad - 1.756G_{ns}(19) \tag{7}$$

where the gradients (G) are given in meters. It can be noted in (7) that both east/west and north/south gradients contribute to the meridional displacement. The primary reduction of variance, of course, is provided by east-west gradients.

Table 2 Predictors (P) and regression coefficients (RC) required for computing the meridional component of steering displacement. Column labeled (RV) gives the incremental reduction of variance based on dependent data. See Figure 2 and text for description of the specified predictors.

	12 HOUR FORECAST			24 HOUR FORECAST			36 HOUR FORECAST			48 HOUR FORECAST			72 HOUR FORECAST		
INDEX	P(J)	RC(J)	RV(J)	P(J)	RC(J)	RV(J)	P(J)	RC(J)	RV(J)	P(J)	RC(J)	RV(J)	P(J)	RC(J)	RV(J)
J=0(Intercept)	....	46.4248	.....	....	94.1272	.....	....	137.4948	.....	....	199.6654	.....	....	-12151.3047	.....
J=1	17EW	-1.3077	0.273	17EW	-2.5992	0.290	17EW	-5.3417	0.290	17EW	-7.0224	0.275	17EW	-10.1938	0.226
J=2	12EW	-2.3705	0.122	12EW	-4.9091	0.085	12EW	-5.2674	0.062	12EW	-5.9534	0.043	TKNS	4.1619	0.035
J=3	2EW	-1.5110	0.051	2EW	-1.4598	0.038	....	......	.....	....	......	.....	22NS	4.3467	0.066
J=4	8NS	1.5385	0.043	2NS	3.3023	0.036	....	......	.....	....	......	.....	....	......	.....
J=5	19NS	-1.1750	0.035	19NS	-2.3564	0.034	....	......	.....	....	......	.....	....	......	.....
Total variance reduction			0.524			0.484			0.352			.0.318			0.326

Table 3 Predictors (P) and regression coefficients (RC) required for computing the zonal component of steering displacement. Column labeled (RV) gives the incremental reduction of variance based on dependent data. See Figure 2 and text for description of the specified predictors.

	12 HOUR FORECAST			24 HOUR FORECAST			36 HOUR FORECAST			48 HOUR FORECAST			72 HOUR FORECAST		
INDEX	P(J)	RC(J)	RV(J)	P(J)	RC(J)	RV(J)	P(J)	RC(J)	RV(J)	P(J)	RC(J)	RV(J)	P(J)	RC(J)	RV(J)
J=0(Intercept)	....	-10.3112	.....	....	33.1046	.....	....	7.7343	.....	....	15.9870	.....	....	24.8811	.....
J=1	21NS	-1.7035	0.528	23NS	-3.3927	0.479	23NS	-5.6318	0.448	15NS	-5.1030	0.412	11NS	-9.8069	0.323
J=2	4NS	-3.0025	0.142	4NS	-2.8553	0.183	4NS	-5.1563	0.173	4NS	-8.3596	0.111	20NS	8.1782	0.096
J=3	9EW	-1.3774	0.067	17EW	2.6716	0.038	17EW	3.3777	0.047	16EW	7.4307	0.069	3EW	-7.8882	0.051
J=4	....	......	.....	20NS	-2.5260	0.040	....	......	.....	....	......	.....	....	......	.....
Total variance reduction			0.737			0.740			0.668			0.592			0.470

C. The synoptic forecasts

1) <u>Data bed and grid system</u>. The National Hurricane Research Laboratory (NHRL) of ERL, NOAA, maintains and continuously updates a master hurricane data tape. Residing on this tape are the current and the 24-hour old 1000, 700, and 500 mb. geopotential height fields for approximately 1000 tropical cyclone forecast situations dating back through the year 1945. The height fields are defined by an approximately storm-centered 8 x 15 grid system as illustrated in Figure 3.

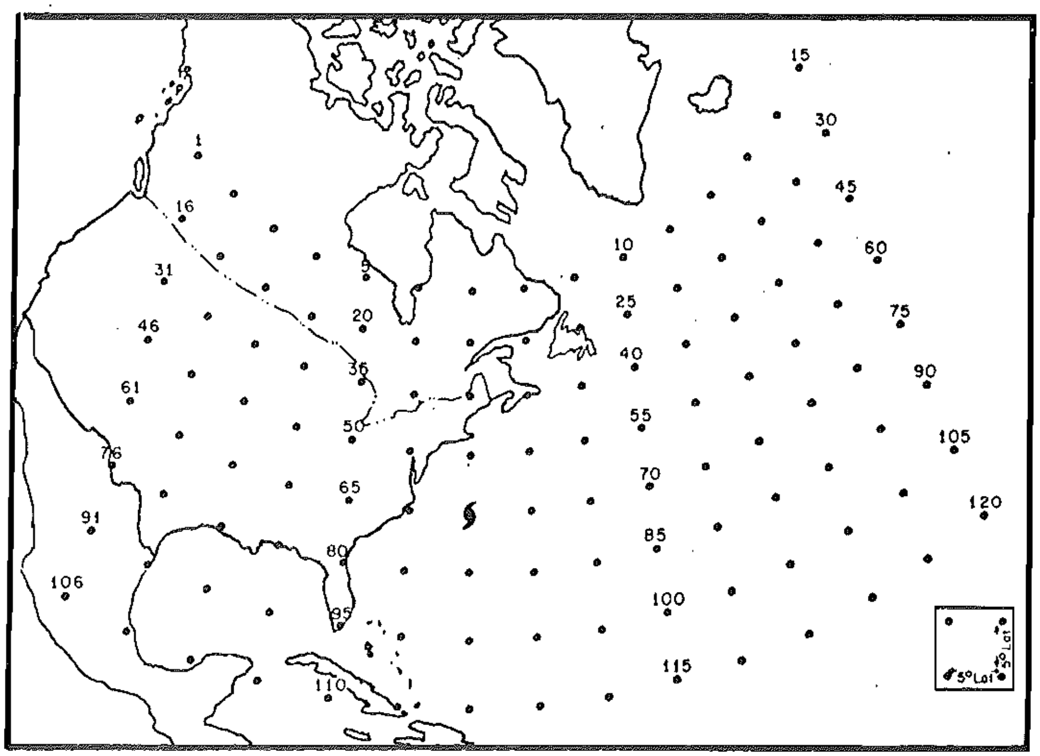


Figure 3. The location of the 120 grid-points for a storm centered at 35N, 70W. Grid spacing is 300 n.mi.

In order to meet the data requirements of the NHC73 system, it was necessary to restructure the data tape so that each individual forecast situation contained not only the current (T + 0) grid data but also the later observed 500 mb. heights after 24 hours (T + 24), after 36 hours (T + 36) and after 48 hours (T + 48). The 500 mb. heights at T + 24, for example, were found by looking ahead two cases on the data tape, the T + 36 by looking ahead three cases and the T + 48 by looking ahead four cases. However, this "future" data makes reference to the "future" position of the storm. Since this latter position is not known operationally, it was necessary to reposition the observed grids with reference to the observed storm center at time T + 0 rather than at T + ΔT. A double linear interpolation scheme was used for this purpose.

Missing data eliminated many of the forecast situations from consideration and a final revised data tape contains 530 cases. Each case, in addition to storm identification and displacement data, contains the initial 1000, 700 and 500 mb grid fields and the T + 24, T + 36 and T + 48 hour observed 500 mb. grid fields. All the data are reference the T + 0 position of the storm according to the grid system shown in Figure 3.

2) The stratification scheme. Experience with previous objective systems has shown that improved performance can be attained by employing some type of data stratification. The NHC72 system (Neumann, et al, 1972), uses a stratification scheme based on the initial motion of the storm. A later study, Hope and Neumann (1973) indicates that while such a system gives superior results based on dependent data, operational limitations in the specification of initial motion often compromise the results. There is always the danger that the wrong set of prediction equations will be used. A geographical stratification is considered less sensitive to initial data errors than would be a system based on initial motion. Accordingly, the

NHC73 system uses a geographical stratification.

One deficiency of any stratification system is that sudden discontinuities in the hurricane track forecast can occur when the program automatically shifts from one set of prediction equations to another. Two methods are available to avoid such an occurrence. One method involves the assignment of weighting factors to each set of prediction equations. The other method involves overlapping the sub-sets of data in such a way that adjacent sets contain many of the same cases. Both of these methods are used in the NHC73 system.

Details of the scheme are illustrated in Figure 4. The hurricane belt across the Atlantic, Caribbean and the Gulf of Mexico is subdivided into 52 areal zones. The centers of zone 1 through zone 50 are as shown on Figure 4. Zone 51 includes all storms north of 34N while zone 52 includes all storms south of 18N. These 52 zones were selected after a careful analysis of computer capability and operational data limitations. The storms in zone 52, for example, are far enough south that the lower three rows of grid points (see Figure 3) on the storm centered grid are not available on an operational basis. These require special treatment in that predictors from these rows must be forced out of the regression analysis. The storms near the bottom row of zones (1, 6, 11,.....46) cannot use predictors in the lower two rows of grid points, etc. Storms east of 45W will not be forecast by the NHC73 system due to the lack of sufficient dependent data.

The dots plotted on Figure 4 give the initial location of the 530 cases comprising the entire dependent data set. It is obvious from the unequal density distribution of these storms that any fixed circular area around each zone would encompass a varying number of storms. A circular area say, 5 degrees in radius would include sufficient cases east of Florida and in the Bahamas but in the Gulf of Mexico and elsewhere in the Atlantic there would be

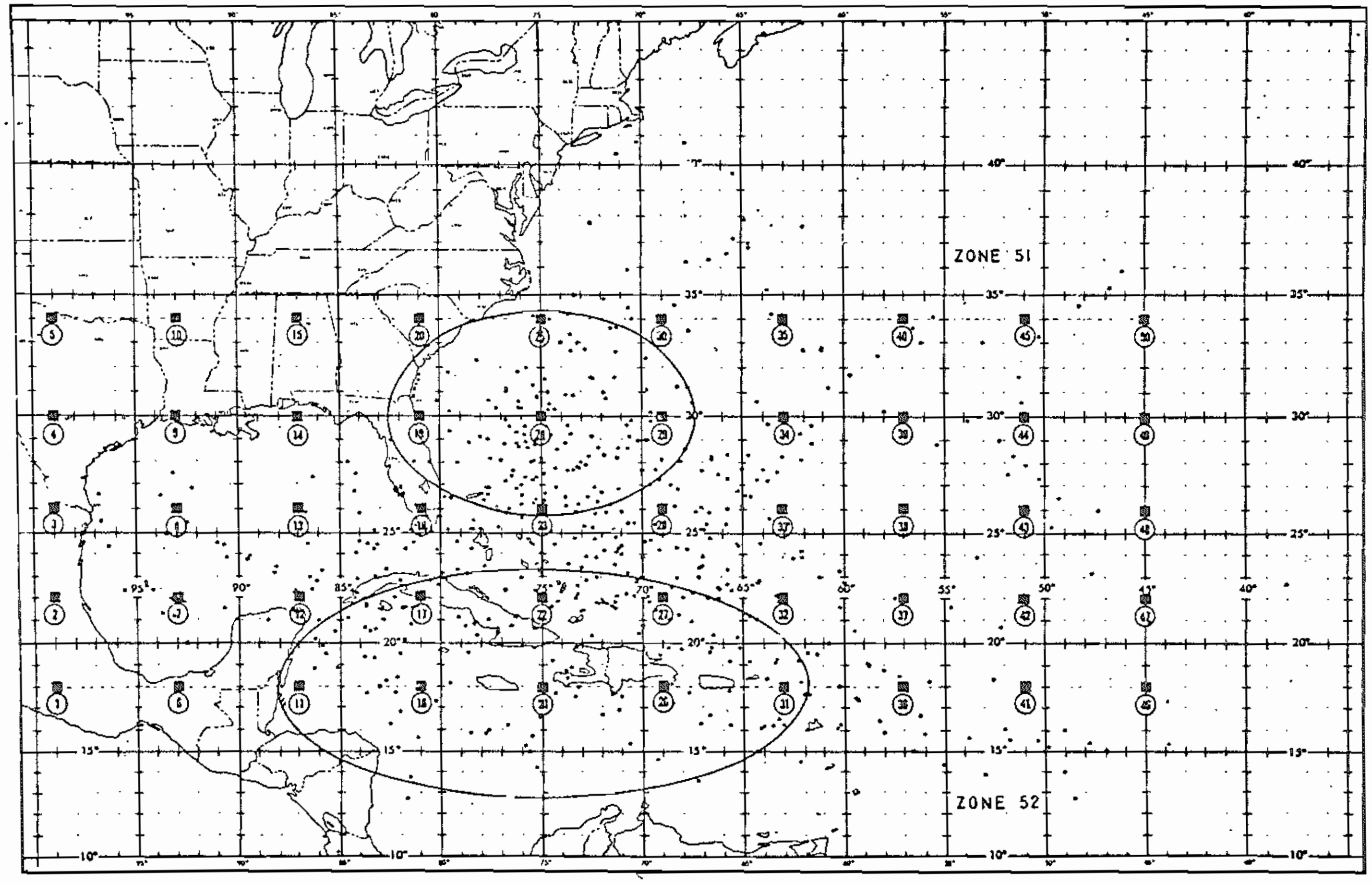


Figure 4. Location of the 52 stratification zones. The ellipses show the geographical bounds of zone 21 and zone 24. Dots show the initial position of the 530 tropical cyclones comprising the dependent data set.

insufficient cases for a statistical analysis. Accordingly, an elliptical scanning technique was used.

The size of the elliptical scanning area centered on each of the 50 zones was increased in stepwise fashion until each zone included exactly 127 dependent data cases, this latter figure being the minimum number acceptable by the screening program. The major (east/west) axis of the ellipse was increased at a faster rate than the minor (north/south) axis according to,

$$A = (B-3)^{2.5} + B \tag{8}$$

where A is the length of the major axis and B is the length of the minor axis. The logic behind the selection of (8) is related to the fact that, insofar as motion characteristics are concerned, storms at different latitudes have less in common than storms at different longitudes. In no case was it considered advisable to look more than 400 n.mi. north or south of a zone center for storms with common motion characteristics.

The particular ellipses used for selection of 127 cases representing zone 24 and zone 21 are shown in Figure 4. The largest ellipses were used at zone 2 and zone 47. In these latter zones, the size of the east/west axis becomes so large in relation to the north/south axis that the stratification essentially includes all storms within a twelve degree latitude belt centered on 22N. This is considered a desirable feature of equation (8).

A separate set of screening equations was developed for each of the 52 zones shown in Figure 4. In operational practice, the prediction equation sets from four zones nearest the current storm position are used to compute the forecast displacement. Further details on this latter point will be discussed in Section 3.

3) <u>Test screening runs</u>. Before finalizing the program to perform the

synoptic screening analysis, several test screenings were performed. The purpose of these tests was to give some insight into expected system performance using "prognostic" heights as predictors in lieu of 24-hour old data as had been used in previous statistical systems. The tests were conducted on 127 hurricanes and tropical storms forecast situations with initial positions north of latitude 28N.

Table 4 Analysis of forecast errors using predictors derived from perfect-prog 500-mb. heights in lieu of predictors derived from 24-hour old data. See Table 5 for description of specified predictor sets.

	12 HR	24 HR	36 HR	48 HR	72 HR
Mean displacement error (n.mi.) without "prognostic" data (Predictor SET A).....	30	67	111	157	245
Percentage decrease in displacement error using:					
Predictor SET B......	6%	7%	14%	21%	24%
Predictor SET C......	17%	21%	27%	26%	26%
Predictor SET D......	10%	13%	19%	17%	19%

Table 5 Description of predictor sets referenced in Table 4

	SET A	SET B	SET C	SET D
1. 1000-mb. analysis......................	X	X	X	X
2. 700-mb. analysis......................	X	X	X	X
3. 500-mb. analysis......................	X	X	X	X
4. 1000-mb. 24-hr. height changes..........	X	X		
5. 700-mb. 24-hr. height changes..........	X	X		
6. 500-mb. 24-hr. height changes..........	X			
7. 24-hr. 500-mb. "prognostic" heights.......			X	
8. 36-hr. 500-mb. "prognostic" heights.......			X	
9. 48-hr. 500-mb. "prognostic" heights.......		X	X	
10. 24-hr. 500-mb. "prog" height changes......				X
11. 36-hr. 500-mb. "prog" height changes......				X
12. 48-hr. 500-mb. "prog" height changes......				X
13. CLIPER (Climatology & Persistence)......	X	X	X	X

Salient features of the test are summarized in Table 4. Initially, a mean displacement[2] error was computed from the predictor set labeled "A" in Table 5. These are the same predictors used in the NHC72 system. Additional screening runs were then made with the other predictor sets as specified in the tables. As anticipated, the test indicated that, based on dependent data, better results are obtained using the "prognostic" data than were obtained using the observed 24-hour old data. The tests show further that the use of 24, 36 and 48 hour data give better results than using the 48

[2]A displacement error is defined as the absolute value of the great circle distance between predicted and observed displacement.

hour "prognostic" data by itself. An unanticipated finding was the fact that the use of heights rather than height changes led to greater percentage reduction in displacement errors. This latter finding suggests that the use of actual heights rather than height changes may improve the variance reducing potential of both the NHC67 and the NHC72 systems, both of which now use height changes as predictors.

4) Synoptic screening runs. Subject to the limitations specified in sub-section 2, above, a total of 720 predictors were available for each of the synoptic screening runs. The six sets of predictors are listed symbolically in Table 6. A standard stepwise screening procedure was used to test the variance reducing potential of each of these predictors. Separate screening runs were made for each of the two orthogonal components of storm motion for each of the five forecast periods, zero to 12 hours, zero to 24 hours, zero to 36 hours, zero to 48 hours and zero to 72 hours.

Table 6 Predictors included in the synoptic regression analysis. The subscript (I) refers to one of the 120 grid-point addresses as specified in Figure 3

Predictor set number	Predictor description	Symbolic form
1	1000-mb. observed height	(H0010(I),I=1,120)
2	700-mb. observed height	(H0007(I),I=1,120)
3	500-mb. observed height	(H0005(I),I=1,120)
4	500-mb. 24-hour forecast height	(H2405(I),I=1,120)
5	500-mb. 36-hour forecast height	(H3605(I),I=1,120)
6	500-mb. 48-hour forecast height	(H4805(I),I=1,120)

It was noted in initial test screenings that the "prognostic" grid-points nearest the up and downstream side of the storm track were always being selected as the prime variance reducers at the expense of grid points further removed from the storm. Because of the nature of the "perfect-prog" method and the desire to incorporate large-scale circulation features into the model, the 8 grid-points surrounding the storm were forced out of the regression analysis.

Because of practical limitations in the screening regression computer program, each of the synoptic prediction equations (10 equations for each of the 52 zones shown in Figure 4), required seven screening runs. The first six runs selected and stored the 20 best predictors from each of the six height fields while the seventh run considered the 120 predictors in the combined set. This final run was programmed to terminate when 12 predictors had been selected. Experience with the NHC72 system indicated that additional predictors failed to offer sufficient incremental reduction of variance. In any case, F-test statistical significance criteria were well satisfied at the one percent level (Burington and May, 1958).

5) Correlation coefficient fields. A large amount of diagnostic information on the behavior of tropical cyclone motion in relation to the surrounding upper-level height fields is contained in the 52 sets of geographical correlation coefficient fields generated by the synoptic screening runs. While it is beyond the scope of this paper to thoroughly discuss these data, a few of the features are worthy of mention.

Figures 5 and 6 illustrate some of the correlation coefficient fields between the geopotential heights and tropical cyclone motion for equation set 22 (zone centered at 22N, 75W). The top panel of Figure 5 shows that there is a well-defined direct relationship between the westerly component of storm motion and the height of the 500 mb. surface centered some 500 n.mi. north of the storm center. Accordingly, the stepwise screening program selected the grid point nearest the center of this feature as one of the 12 grid-points containing height information which is used to empirically predict 24-hour zonal storm motion.

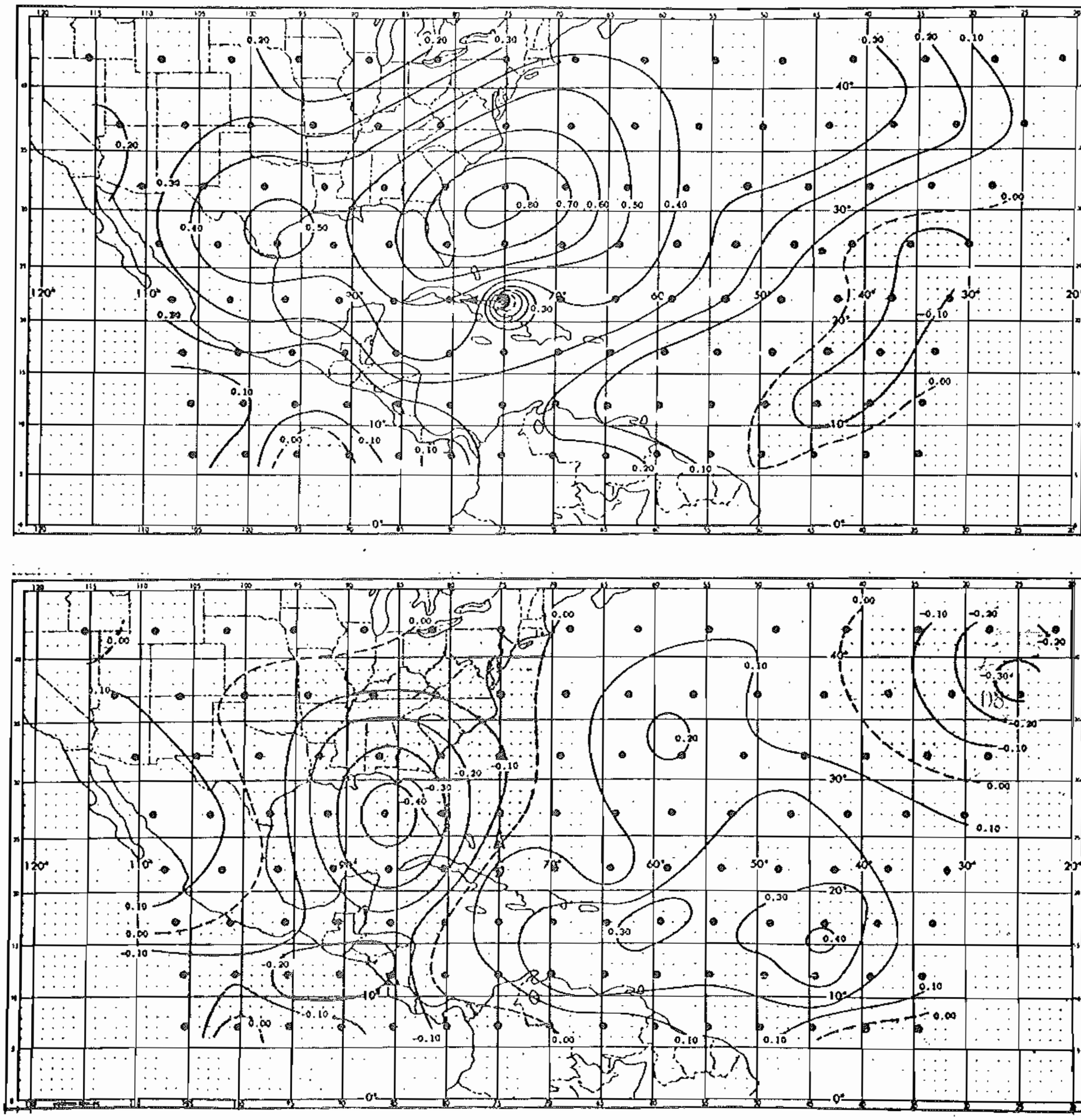


Figure 5. Linear correlation coefficient field between current 500 mb. heights and the 24-hour meridional (BOTTOM) and zonal (TOP) tropical cyclone displacement. Shading shows areas of negative correlation.

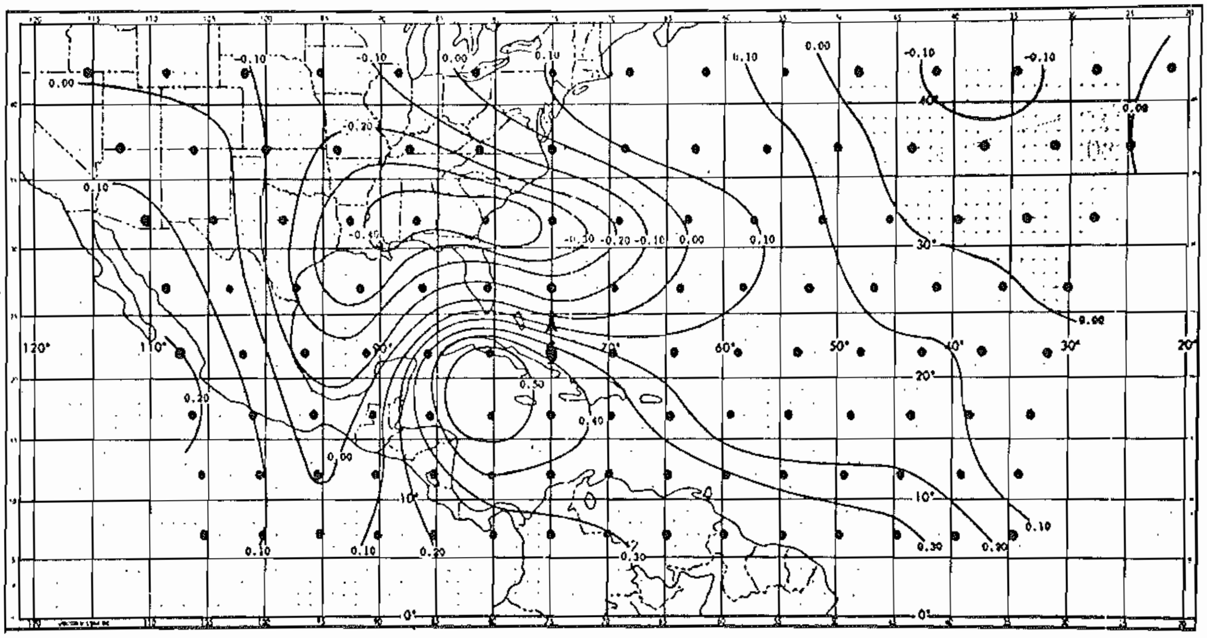


Figure 6. Linear correlation coefficient field between the 500-mb 48-hour "perfect-prog" heights and 48-hour meridional tropical cyclone motion. Shading shows areas of negative correlation.

Similarly, the lower panel of Figure 5 shows that there is an inverse relationship between the 500 mb. heights centered some 700 n.mi. northwest of the storm center and northerly storm displacement. It is significant to note that a single grid point from the top panel is capable of explaining four times as much variance of tropical cyclone motion (the reduction of variance is given by the square of the correlation coefficient) as a single grid point from the lower panel. In this sense, zonal motion is "easier" to statistically predict than is meridional motion.

Figure 6 shows the correlation coefficient field between the 48-hour meridional motion and the 48-hour "prognostic" data. In this case the storm is offset to the southeast of where it would normally be in 48 hours and relatively lower heights to the north and higher heights to the south are associated with northerly motion.

6) Synoptic prediction equations. The array of constants, predictors and predictor addresses used by each of the 52 sets of prediction equations is too large to be listed herein. Instead, those comprising set number 22 (zone centered at 22N, 75W) will be presented and used to illustrate a typical set of synoptic prediction equations.

Table 7 Meridional regression coefficients required by equation set number 22 (22N, 75W)

Predictor Number (J)	12HR FCST (k=1)	24HR FCST (k=2)	36HR FCST (k=3)	48HR FCST (k=4)	72HR FCST (k=5)
J=0 (Intercept)	2143.4794	2096.2676	-13001.0002	-25764.8656	-34955.5167
J=1	0.1671	0.8387	-1.5711	-2.5200	-2.3085
2	-0.7516	1.1068	1.9924	2.5600	2.1858
3	0.5154	0.9906	0.6359	2.4108	1.1806
4	-0.3045	-1.3937	0.8751	-1.2451	2.6456
5	0.3241	0.9258	-2.7678	2.8738	-5.2569
6	-0.4267	0.8603	1.6961	-4.0151	-1.3330
7	0.2348	-0.2422	-0.5571	-2.6296	2.7805
8	0.3818	-1.1666	2.2307	1.8813	-3.9428
9	0.1297	0.3236	0.6422	-0.6654	2.8672
10	-0.1348	-0.3991	0.4243	1.9478	3.3250
11	-0.0988	0.9916	-0.2276	-1.2343	2.5838
12	0.1368	-0.6719	-0.7226	0.6708	-1.3770

Table 8 Variance analysis of meridional motion predicted by equation set number 22 (22N, 75W)

Predictor Selection Order	12 HOUR FCST (k=1)		24 HOUR FCST (k=2)		36 HOUR FCST (k=3)		48 HOUR FCST (k=4)		72 HOUR FCST (k=5)	
	Predictor	RV	Predictor	RV	Predictor	RV	Predictor	RV	Predictor	RV
J=1	H4805(65)	0.167	H2405(50)	0.183	H2405(50)	0.241	H2405(50)	0.254	H2405(50)	0.237
2	H0005(65)	0.145	H4805(80)	0.208	H4805(80)	0.196	H4805(80)	0.175	H2405(47)	0.148
3	H0007(84)	0.188	H2405(84)	0.098	H2405(84)	0.073	H0007(61)	0.076	H3605(73)	0.091
4	H0005(30)	0.046	H0005(65)	0.058	H0007(61)	0.049	H0010(61)	0.046	H0005(85)	0.042
5	H2405(56)	0.038	H0007(61)	0.054	H0005(65)	0.047	H0005(88)	0.047	H0010(80)	0.061
6	H2405(50)	0.028	H0007(84)	0.029	H0005(64)	0.026	H0010(80)	0.057	H4805(37)	0.031
7	H0010(63)	0.022	H0005(14)	0.026	H4805(37)	0.027	H0007(95)	0.029	H2405(22)	0.030
8	H2405(97)	0.019	H0005(94)	0.022	H3605(96)	0.026	H4805(102)	0.025	H2405(37)	0.028
9	H2405(13)	0.017	H4805(30)	0.020	H3605(22)	0.023	H0005(19)	0.023	H4805(99)	0.029
10	H4805(38)	0.014	H3605(36)	0.021	H4805(30)	0.015	H0007(63)	0.010	H4805(76)	0.025
11	H2405(2)	0.018	H3605(96)	0.017	H0005(14)	0.013	H4805(35)	0.009	H0010(58)	0.015
12	H0007(30)	0.015	H2405(86)	0.016	H3605(36)	0.011	H3605(21)	0.016	H3605(50)	0.018
Total Reduction		0.717		0.751		0.747		0.767		0.756

The general prediction equation for meridional motion (DY) in units of nautical miles at the time period k is given by,

$$DY(k) = C(0,k) + \Sigma \quad C(j,k)P(j,k) \qquad (9)$$
$$j = 1,12$$
$$k = 1,5$$

where the regression coefficients C(j,k) are listed in Table 7 and the corresponding predictors and predictor addresses are listed in Table 8. The symbolic form of each of the six predictors was defined in Table 6 while the predictor grid addressing system was defined in Figure 3. For example, the first predictor listed in Table 8, H4805(65), refers to the 48-hour forecast height (meters) of the 500 mb. surface at a point 600 n.mi. west of the storm center.

Similarly, the general prediction equation for zonal motion (DX) at time period k is given by,

$$DX(k) = C(0,k) + \sum_{\substack{j = 1,12 \\ k = 1,5}} C(j,k)P(j,k) \tag{10}$$

where the regression coefficients C(j,k) are given in Table 9 and the corresponding predictors and predictor addresses are given in Table 10. The empirical equations (9) and (10) provide estimates of tropical cyclone forecast motion based entirely on predictors derived from observed and "forecast" upper air data.

Table 9 Zonal regression coefficients required by equation set number 22 (22N, 75W)

Predictor Number (J)	12HR FCST (k=1)	24HR FCST (k=2)	36HR FCST (k=3)	48HR FCST (k=3)	72HR FCST (k=5)
J=0 (Intercept)	-2702.9742	-12571.7371	-17590.5607	-41414.6020	3547.7615
J=1	0.2160	1.4904	1.2033	2.7205	3.1453
2	0.6605	1.5330	-1.7152	-1.9887	-1.9187
3	-0.7281	-1.2504	2.7178	-1.2496	-4.8937
4	0.4215	-0.9277	-1.8508	2.4527	-3.1576
5	-0.2406	-0.4296	1.5551	-1.6095	2.1398
6	-0.2189	0.4318	-1.0909	-2.2875	2.6191
7	-0.4140	-0.5699	-0.7107	2.3443	2.1614
8	0.5879	0.2729	-0.9485	0.8202	-2.0359
9	0.1108	1.4943	0.5252	1.4327	1.1821
10	0.6424	-1.1688	-0.3234	-0.8807	-0.7271
11	-0.4463	0.5933	0.3874	1.7458	-6.4852
12	-0.2548	-0.5348	1.1655	1.3660	5.4182

Table 10 Variance analysis of zonal motion predicted by equation set number 22 (22N, 75W)

Predictor Selection Order	12 HOUR FCST (k=1)		24 HOUR FCST (k=2)		36 HOUR FCST (k=3)		48 HOUR FCST (k=4)		72 HOUR FCST (k=5)	
	Predictor	RV	Predictor	RV	Predictor	RV	Predictor	RV	Predictor	RV
J=1	H0005(37)	0.626	H2405(37)	0.643	H2405(37)	0.665	H2405(37)	0.659	H2405(37)	0.515
2	H0005(52)	0.043	H0005(37)	0.064	H0010(74)	0.052	H0005(88)	0.073	H0005(88)	0.132
3	H0010(75)	0.055	H0010(75)	0.042	H0005(37)	0.044	H4805(65)	0.042	H4805(80)	0.047
4	H3605(54)	0.031	H2405(22)	0.038	H0005(103)	0.034	H3605(54)	0.040	H0005(46)	0.052
5	H4805(50)	0.031	H4805(42)	0.021	H3605(54)	0.020	H3605(56)	0.034	H4805(37)	0.035
6	H4805(40)	0.020	H3605(38)	0.023	H4805(41)	0.024	H0010(74)	0.017	H0005(37)	0.030
7	H0005(88)	0.014	H3605(65)	0.016	H4805(65)	0.022	H2405(94)	0.017	H3605(54)	0.019
8	H0010(52)	0.013	H4805(01)	0.015	H0007(22)	0.022	H3605(01)	0.010	H0010(75)	0.022
9	H4805(13)	0.012	H3605(64)	0.011	H3605(01)	0.009	H0005(37)	0.007	H4805(01)	0.015
10	H2405(54)	0.012	H4805(80)	0.009	H0005(03)	0.011	H2405(31)	0.011	H3605(03)	0.013
11	H4805(80)	0.012	H3605(54)	0.009	H4805(37)	0.007	H2405(77)	0.005	H3605(80)	0.006
12	H2405(57)	0.008	H3605(50)	0.009	H2405(77)	0.006	H3605(98)	0.005	H3605(79)	0.011
Total Reduction		0.879		0.900		0.917		0.922		0.897

D. Combining CLIPER, steering and synoptic components

Following the algorithm of Figure 1, the final combined forecast displacement (D_f) is obtained by combining the CLIPER forecasts (D_1) with the steering forecasts (D_2) and the synoptic forecasts (D_3). In order to effect some coupling between time adjacent synoptic forecasts, the displacement at T - 12 hours or T - 24 hours (D_4) and at T + 12 or T + 24 hours (D_5) were also considered in the final combined forecast such that for the 24, 36 and 48 hour final forecast displacements,

$$D_f = f(D_1, D_2, D_3, D_4, D_5) \tag{11}$$

while for the 12-hour displacement forecast,

$$D_f = f(D_1, D_2, D_3, D_5) \tag{12}$$

and for the 72-hour forecast displacement,

$$D_f = f(D_1, D_2, D_3, D_4). \tag{13}$$

Experience with the NHC72 system has shown that using the synoptic forecasts in this manner helps to smooth out any forecast track discontinuities.

The functions (11), (12) and (13) were estimated by fitting to an equation of the type,

$$D_f = C_0 + C_1D_1 + C_2D_2 + C_3D_3 + C_4D_4 + C_5D_5 \tag{14}$$

where the constants C_0 through C_5 were obtained by least squares techniques. Tables 11 and 12 give the value of these constants for equation set number 22. For example, the final 24-hour forecast meridional motion (DY_{24}) is given by,

$$DY_{24} = -18.0 - .037D_2 + .340D_1 + .352D_4 + .218D_3 + .272D_5 \tag{15}$$

Table 11 Regression coefficients for combining steering, CLIPER, and synoptic forecasts into a final NHC73 forecast displacement. (Meridional motion, equations set 22)

PREDICTOR	12 HR	24 HR	36 HR	48 HR	72 HR
Intercept	-5.4161	-18.0142	-34.1672	-43.7942	-13.5658
Steering forecast	-0.0151	-0.0373	-0.0286	-0.0368	-0.0100
CLIPER forecast	0.5276	0.3404	0.2522	0.1408	-0.0520
Synoptic forecast at T-12 or T-24 hrs	------	0.3516	0.2130	0.4076	0.6593
Synoptic forecast at T=0 hrs	0.3125	0.2181	0.3461	0.4690	0.6928
Synoptic forecast at T+12 or T+24 hrs	0.1163	0.2722	0.3212	0.1674	------

Table 12 Regression coefficients for combining steering, CLIPER, and synoptic forecasts into a final NHC73 forecast displacement. (Zonal motion, equation set 22)

PREDICTOR	12 HR	24 HR	36 HR	48 HR	72 HR
Intercept	1.3176	3.1115	-1.0962	7.7246	-26.8811
Steering forecast	-0.0547	-0.1057	-0.0281	-0.0134	-0.0532
CLIPER forecast	0.3728	0.2714	0.1612	0.0995	-0.0294
Synoptic forecast at T-12 or T-24 hrs	------	0.3631	0.4548	0.4285	0.3781
Synoptic forecast at T=0 hrs	0.4502	0.3312	0.2736	0.3468	0.7955
Synoptic forecast at T+12 or T+24 hrs	0.1248	0.2150	0.2525	0.2006	------

Examination of the other 51 sets of constants corresponding to those given in Tables 11 and 12, shows that there are considerable time and space variations in the weights given to the various displacement forecasts. The weighting of the T + 0 synoptic forecasts generally increases with increased forecast interval while the corresponding CLIPER forecasts are weighted progressively less. The steering forecasts in zone 22 are not weighted very heavily in any time period.

3. OPERATIONAL SELECTION OF APPLICABLE PREDICTION EQUATIONS

Figure 7 shows an enlarged portion of figure 4 with a hurricane centered at 23N, 77W. Since the storm is closest to the center of zone 22, a priori reasoning suggests the selection of equation set number 22 as most appropriate for prediction of the future motion of this storm. However, other selection criteria could also be specified. For example, a double interpolation scheme could be used to weight the predicted displacement inversely as the distance from the four (17, 18, 22, 23) surrounding zone centers. Table 13 shows some results obtained by re-forecasting the displacement of the entire set of 530 dependent data storms according to four specified criteria.

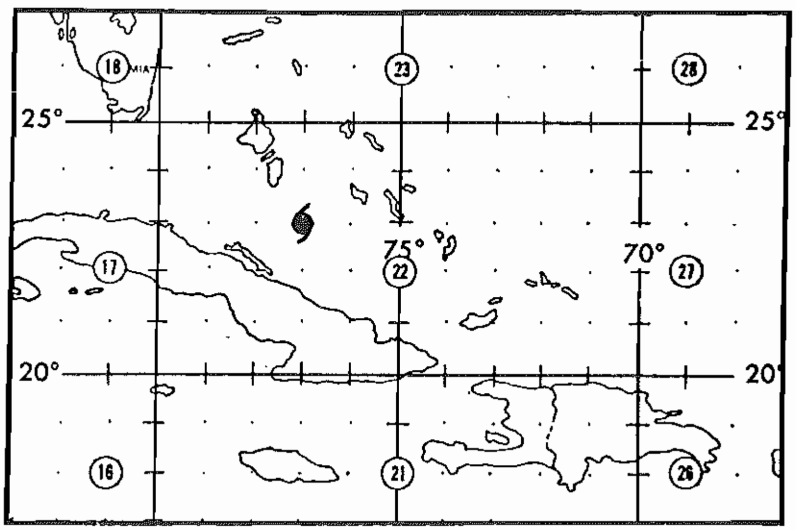


Figure 7. Enlarged section of figure 4 with hurricane centered at 23N, 77W.

Table 13 Average displacement error (n.mi.) using specified weighting functions

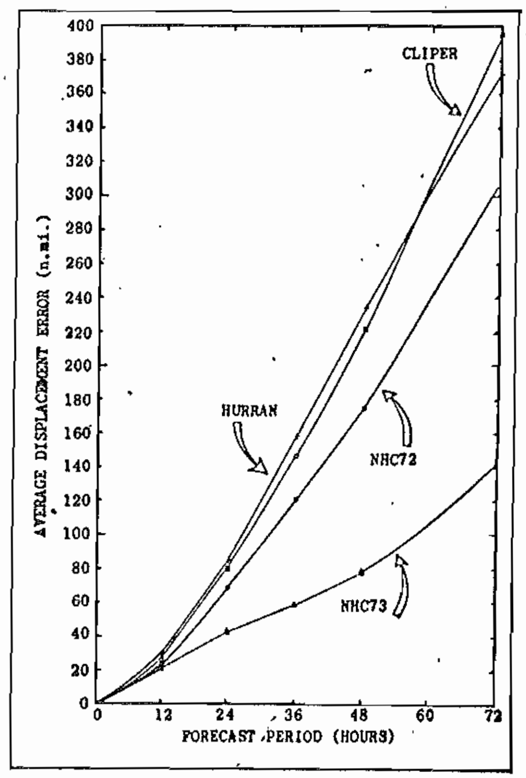
	12 HR	24 HR	36 HR	48 HR	72 HR
Type A weighting.................. (Double linear interpolation)	21	42	59	79	147
Type B weighting.................. (Use the nearest grid point)	22	46	66	88	164
Type C weighting.................. (Each grid point weighted 25%)	21	42	58	78	142
Type D weighting.................. (SW grid point weighted 100%)	23	46	66	88	164

The data show that significantly better results were obtained by equal weighting of the displacements predicted at each of the four nearest zone centers. Accordingly, the prediction algorithm was set up in this manner. In the case of storms south of latitude 18N, equation set 52 was used without any weighting whereas for storms north of latitude 34N, equation set 51 was used. No attempt will be made to forecast storms east of longitude 45W.

Table 14 Average displacement errors (n.mi.) of specified tropical cyclone prediction systems based on development data.

Prediction system	12 HR	24 HR	36 HR	48 HR	72 HR
NHC-72	23	68	120	175	308
HURRAN	30	84	158	234	372
CLIPER	25	80	146	222	395
NHC-73	21	42	58	78	142
Percentage improvement of NHC-73 over NHC-72.	9%	38%	52%	55%	54%

Figure 8. Residual errors of NHC73 compared to other statistical forecasting systems



4. PREDICTION ERRORS USING DEPENDENT DATA

Tables 14 and 15 give detailed analyses of the residual errors after application of the weighting algorithm discussed in Section 3. The data from Table 14 are depicted graphically in Figure 8. It is immediately apparent from this latter figure that the residual errors of the present system are small when compared to those from other recently developed statistical techniques and reflect the use of the perfect-prog data in lieu of actual prognostic heights in the prediction equations. These can probably be considered to be the minimum possible errors one can ever hope to attain in using statistical prediction systems. The use of real prognostic data will certainly degrade the results; the actual amount of degradation must await testing the program in an operational environment.

Table 15 Performance analysis of NHC-73 based on dependent data set. (530 cases) Errors and displacements are in nautical miles.

	12 Hour	24 Hour	36 Hour	48 Hour	72 Hour
Standard error					
Meridional motion......................	18	33	46	61	109
Zonal motion...........................	19	35	51	69	123
Reduction of variance (%)					
Meridional motion......................	87	87	89	90	87
Zonal motion...........................	95	95	96	95	94
Multiple correlation coefficient					
Meridional motion......................	0.93	0.93	0.95	0.95	0.93
Zonal motion...........................	0.97	0.98	0.98	0.98	0.97
Mean error* (Bias)					
Meridional motion......................	0	1	1	0	-3
Zonal motion...........................	0	1	1	2	-1
Mean absolute error					
Meridional motion......................	13	26	35	47	84
Zonal motion...........................	14	27	39	53	98
Stnd Deviation of observed displacements					
Meridional motion......................	49	95	141	187	305
Zonal motion...........................	83	164	246	327	499
Mean of the observed displacements					
Meridional motion......................	57	116	179	247	405
Zonal motion...........................	35	61	77	82	51
Mean absolute observed displacement					
Meridional motion......................	64	129	197	267	426
Zonal motion...........................	74	143	209	272	401

*Forecast minus observed

Some of the NHC73 residual error data from Table 15 have been plotted on to Figure 9. Also, included on this figure are the comparable residual errors of the other components of the NHC73 system, that is, the CLIPER forecasts, the steering forecasts and the synoptic forecasts. The first three of the four panels on Figure 9 show, respectively, the reduction in variance (RV), the multiple correlation coefficient (R_m), and the standard error of estimate (SE) of the forecast displacements. The fourth (right-hand) panel gives the standard deviation (SD) of the observed displacements, this latter quantity being the same for all of the component systems. The smooth curves connecting data points were objectively drawn using a technique suggested by Akima (1970).

The four quantities selected for illustration on Figure 9 are related according to,

$$RV = R_m^{\ 2} = 1 - (SE)^2/(SD)^2 \quad . \tag{16}$$

A given reduction in variance or multiple correlation coefficient can yield a relatively high or low standard error depending on the value of the standard deviation. Thus, the 72 hour zonal standard error of NHC73 (123 n.mi.) is greater than the 72 hour meridional standard error (109 n.mi.) even though the reduction of variance of the former exceeds the latter.

It is apparent from Figure 9 that zonal motion is associated with considerably greater variance reduction than is the meridional motion and in this sense is "easier" to predict statistically. The meridional variance reducing potential of the CLIPER and the steering equations is seen to be poor beyond 48 hours and most of the burden of prediction in these instances is borne by the synoptic system.

Of particular interest is the tendency for the variance reducing potential

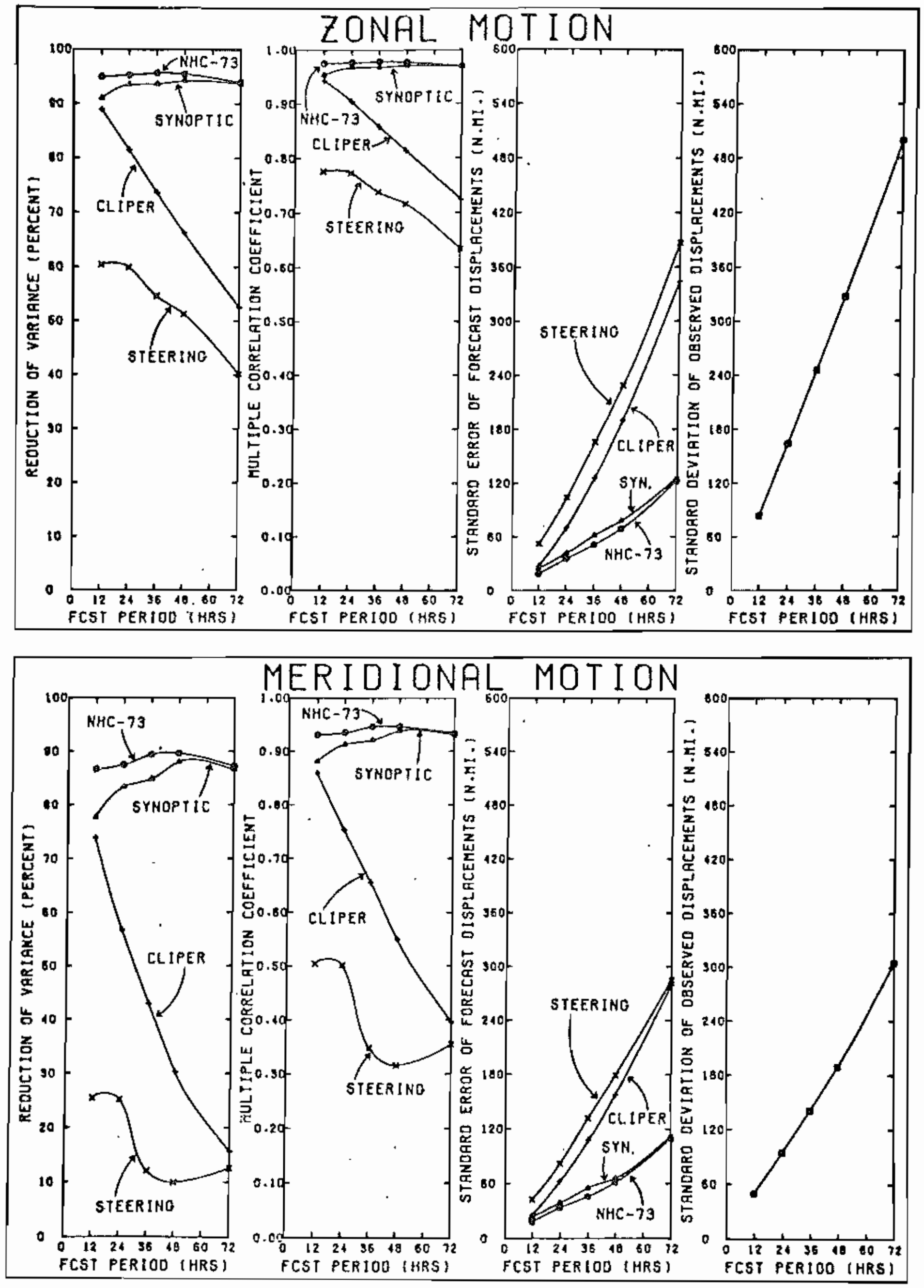


Figure 9. Dependent data error analysis of the NHC73 system

of the synoptic system to increase slightly with time whereas that of the CLIPER and steering systems generally decreases sharply with time. It is not likely that the use of the perfect-prog data brings about this increase, since the same trend was noted in the NHC72 system, where prognostic data are completely lacking.

5. ANTICIPATED REFINEMENTS IN STATISTICAL PREDICTION

The NHC73 system described herein represents a continuing effort by the National Hurricane Center to reduce the errors associated with tropical cyclone prediction. It is hoped that the inclusion of forecast data using the perfect-prog concept will assist in meeting this goal. The next logical step in statistical prediction of tropical cyclone motion is to introduce prognostic data directly into the screening program using the Model Output Statistics (MOS) concept discussed in Section 1B or by employing some type of simulated MOS as suggested by Veigas (1966). It is anticipated that a MOS system will be developed as soon as sufficient dependent data can be collected.

6. ACKNOWLEDGMENTS

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Programming Akima's (1970) curve-fitting technique for an x/y plotter was accomplished by Mr. Peter Chase of the National Hurricane Research Laboratory (NHRL). The latter organization also supplied the magnetic tape which contains the dependent synoptic grid data.

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